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6. AUTHOR(S)
Professor Chu

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Stanford Junior University
857 Serra Street Rm 260
Stanford, CA 94305-4125

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13. ABSTRACT *(Maximum 200 words)*

A number of atom interferometry metholds have been introduced and the state of the art in precision atom interferometry have been advanced. An interferometer using laser cooled atoms in an atomic fountain and off-resonant optical Raman pulses between ground states of the atom has been applied to the measurement of the ratio of Planck's constant to mass, which is a step in the determination of the fine structure constant. The result has surpassed the next best measurement (the Quantum Hall Effect measurement) by a factor of ten in precision. Also, using an atomic interferometer as an accelerometer, the value of g has been measured and compared to that of the previous best absolute gravimeter (based on a falling corner-cube optical interferometer) with comparable results.
Using "optical tweezers" based on laser trapping techniques, experimental verification of the reptation theory of polymer dynamics, develped by de Gennes twenty-five years ago, have been achieved. Other techniques and measurements have been unable to provide the needed verification.

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Final Technical Report for AFOSR grant F49620-95-1-0023
(10/1/94 to 10/1/97) Steve Chu

1) Atom interferometry

During this granting period, we introduced a number of atom interferometry methods and advanced the state of the art in precision atom interferometry.

In a long article in Applied Physics B[1], we gave the details of our experiment to measure $\hbar$/M by measuring the frequency shift due to the recoil of a single photon momenta. The interferometer used laser cooled atoms in an atomic fountain and off-resonant optical Raman pulses between ground states of the atom, a technique we introduced in the previous granting period. This method of atom interferometer has yielded the most precise atom interferometry measurements. The paper included a comprehensive discussion of the systematic effects that could affect the four $\pi/2$ pulse interferometer we used.

We examined theoretically ac Stark shifts and transfer efficiencies using the adiabatic transfer method first used to transfer populations in molecular states by the Bergman group.[2] We showed that atoms with a single excited state and two ground states can be transferred via a "dark state" with no Stark shift, even if there is a non-adiabatic component to the transfer process. (The two light-shifted states experience equal but opposite Stark shifts that cancel.) Also, by directly integrating the Schrödinger equation, we calculated the expected transfer efficiency and ac Stark shifts using the adiabatic transfer method between the $S_{1/2}$ and $P_{1/2}$ states of cesium.

We demonstrated the first atom interferometer based on "dark state" adiabatic transfer.[3] Unlike the previous work on adiabatic transfer where the intensity change of the two light pulses was governed by the passage of an atomic beam of atoms through two spatially separated gaussian beams, we used optical pulses switched on and off by an acousto-optic modulator. This allowed us to tailored the intensity profile of the two light beams independently and construct the necessary atom optics components needed in an atom interferometer. In the same paper, we reported a transfer efficiency of 98.6% for Doppler-free transitions and 95% for Doppler-sensitive transitions. We demonstrated that it was possible to add coherently over 300 hundred photon momenta to an ensemble of atoms.

Using our new adiabatic transfer interferometer, we are now finishing a precision measurement of $^4\hbar$/M.[5,6,7] So far, the precision has been improved by at least a factor of 200 compared to our first generation experiment. With recent improvements, we seem to be free of systematic effects down to the 2 part per billion level. We are still searching for systematic effects, but if this result holds up, it will have surpassed the Quantum Hall Effect measurement of α (best direct measurement of the fine structure constant) by a factor of 10. This work is at the leading edge of precision atom interferometry: currently, we exceed the next best the best absolute measurement of any physical quantity by four orders of magnitude.

In another atom interferometer experiment, we have measured g, the acceleration due to gravity on an atom with a short term precision in $\Delta g/g$ of 2×10^{-9} after one minute of integration time.[5,6,7] We also have been able to automate the operation of our gravimeter interferometer so that it can be kept running continuously for a week or longer. Since the local value of g changes by roughly one part in 10^7 due to tidal forces from the moon, sun and the planets, a measure of the long term stability of this instrument depends on how well the tidal forces are understood. By comparing extended time records of g to a tidal model that also incorporates the ocean loading of the tectonic plates, we have been able to fit our data to the model with a precision of one part in 10^{10}. Since our atom interferometer is an improvement over existing gravimeters, it is not clear that the uncertainty in the fit is due to our instrumental drifts or to the inadequacies of the tidal model.

We also have run our interferometer simultaneously with the best absolute gravimeter based on a falling corner-cube optical interferometer. (model XXX run by the NOAA) for three days in our

laboratory. We found that our short term stability exceeds the performance of this gravimeter that has been developed and refined over the past twenty years. Our measurement of the absolute value of g is consistent with the falling corner cube gravimeter to an uncertainty of ~5 parts per billion. We are finishing the complete set of checks for systematic effects. The absolute accuracy of the commercial gravimeter is specified to be in the range of 2-3 parts per billion uncertainty while the transfer measurement of g (from where our atoms fall in the lab to where the corner cube falls) has an uncertainty of 5 parts per billion. By comparison, a one ppb change in g is equivalent to a change of 3 millimeters from the center of the Earth.

In order to achieve the type of accuracy, we used interferometer free fall times of up to 0.4 seconds. During this time, mechanical vibrations of the mirror mounts and other optical components add phase noise to the optical fields used to induce the Raman transitions. We designed and constructed a low frequency vibration isolation platform that reduced vibrations in the rage from 0.01 - 50 Hz by roughly two orders of magnitude over passive isolation.[8] With this platform, we could then compare the frequencies of the two Raman beams (and also the frequencies of the two adiabatic transfer beams) and correct for the phase shifts due to all lab vibrations in a feedback system that controlled the frequency of one of the laser beams. This vibration isolation platform may be one of the best low frequency vibration isolation platforms available. Using the platform, we were able maintain 98% of the interferometer fringe contrast at the longest drop times used relative to our shortest drop times; without it, our fringes disappeared after 60 msec.

3) Optical trapping and laser cooling

We constructed a number of far de-tuned blue optical traps based on the construction of repulsive optical sheets of light. In our first trap, we achieved atomic coherence time of 4 seconds as measured by microwave Ramsey spectroscopy.[9] This trap compares favorably with far red de-tuned traps such as a dipole trap based on two crossed, focused beams.[10] In the latter trap, we demonstrated the first evaporative cooling from an optical trap.

In a more refined version of the blue-de-tuned trap in the form of an inverted pyramid, atoms were Raman laser cooled to below the single photon recoil limit without loss of atoms.[11,12] Some of these trapping results were summarized in a conference proceeding of the 14th International Atomic Physics Conference.[13] We have also demonstrated Raman cooling to the photon recoil limit where the atoms were simultaneously spin polarized.[14]

Using these techniques, we were able to cool and trap 0.7 million atoms with a phase space density 500 times greater than the phase space density obtainable in a dark MOT trap and a factor of 200 away from Bose condensation. Unfortunately, we are plagued with unidentified heating of the atoms (~300 nanoKelvin/sec) that prevents us from evaporatively cooling to the phase transition. In our efforts to eliminated potential heating mechanisms, we have intensity and mode stabilized the high powered argon laser beam by passing it through an efficient Fabry-Perot mode filter, but this work did not reduce the heating rate.[15]

A general talk summarizing the advances in laser cooling and trapping was given.[16]

3) Polymer physics at the single molecular level

The technique we developed to manipulate single molecules of DNA with lasers has been applied to polymer physics and bio-physics.

Our first experiment, published during the beginning of the granting period, showed the existence of tube-like motion by imaging the relaxation of a single stained molecule of DNA in an entangled polymer solution of unstained polymers.[17] This work provided graphic confirmation of the basic assumption of the reptation model of polymer diffusion proposed by de Gennes, Doi and Edwards in 1971, was the cover article in Science. We also published measurements of the relaxation of single molecules of DNA via optical microscopy.[18]

We continued to develop and use techniques to examine and quantitatively measure polymer dynamics. We proved that all of the assumptions of the reptation model were satisfied by showing that the time it takes for a polymer to diffuse into a new tube was less than the life time of the tube defined by the polymers surrounding the test chain.[19] We examined the stretching of DNA molecules in the size range up to 88 μm long in uniform flow.[20] Contrary to expectations, the polymer's resistance to hydrodynamic drag scaled as $L^{0.54}$ instead of the predicted scaling of $L^{1.0}$ for long flexible chains suggested by de Gennes. In collaboration with Ron Larson, we were able to explain the extensional data.[21] We also showed that the good agreement of our data with an overly simplistic but often used "dumbbell model" was due to the fortuitous cancellation of two relatively large physical effects. Our computer simulations suggested that the asymptotic limit of $L^{1.0}$ would be approached for still longer polymers, and by examining the extension of single molecules up to 150 μm long, we showed that the scaling exponent increased to $L^{0.74}$. We showed that the diffusion of DNA in solution in keeping with the dynamical scaling prediction for a polymer in a "good" solution.[22]

By partially extending the ends of a single DNA molecule in a pair of optical tweezers, we recorded the thermal fluctuations of the molecule.[23] Since the molecule could be directly imaged in fluorescence microscopy, we could test the half century hypothesis that the motion of a polymer in solution can be described by a linear set of equation of motion. This "normal mode" description of polymer dynamics is usually considered to be a crude approximation to an inherently non-linear situation. We were able to identify a set of normal modes (up to mode 8) that satisfied all of the requirements demanded by the linear theory. For example, the orthogonality of the modes was as good as the noise floor of our data at the fraction of a percent level. What was surprising was that there was no evidence of non-linear dynamics.

We examined the stretching of single molecules of DNA in a elongational flow field. A sharp "phase" transition in the elongation of a polymer as a function of the velocity gradient of the flow was predicted by de Gennes. After twenty five years after this prediction, a large body of experiments that examined the bulk behavior using a variety of methods including light scattering, optical birefringence and rheology experiments were unable to confirm or refute the existence of this phase transition. By observing the elongation of thousands of individual molecules, we were able to show that those molecules that reached their steady state elongation indeed showed a very sharp transition within 20% of the predicted transition point.[24] We discovered in the course of this work that there were a number of unraveling scenarios with very different dynamics even though particular care was made to insure that the starting conditions and the lengths of the polymers were identical. We have shown that small thermal fluctuations in the initial starting configurations lead to a wide diversity of unraveling geometries. Thus, we showed conclusively that *any* mean-field theory of polymer extension are inadequate. All theories of polymer dynamics have been mean-field theories. In a much longer article (a book chapter) on elongational flows, we also discussed several other findings that are in contradiction with theoretical predictions.[25] Much of the above work has been summarized in a few additional articles.[26,27,28]

Our work as been well received by the polymer community. The polymer work was highlighted

by the AIP "Physics News".[29] Several enthusiastic Science reviewers stated we were "opening a new field". We have given a large number of invited talks at polymer conferences and Gordon conferences, a plenary talk at the annual Rheology conference, a talk on interdisciplinary science to commemorate the 50th anniversary of the Fermi and Franck Institutes, Univ. of Chicago, and the final "summary" talk at the Moretonhampstead High Polymer Conference. One of my polymer students, Steve Quake, is now an Assistant professor in Applied Physics at Cal Tech and another student, Tom Perkins, won the Padden prize for the best polymer thesis for 1997.

4) Biophysics

Our work in developing a acousto-optically controlled optical tweezers that was used in quantitative measurements of the force and displacement.[30] This apparatus was then used in an experiment reported as the cover article in Nature to measure the force and displacement caused by a single myosin molecule when it hydrolyses a single molecule of ATP.

As a prelude to quantitative atomic force microscopy on biologically active molecules, we in collaboration with others, developed an atomic flat surface that is functionalized where proteins and other bio-molecules can be attached with specific covalent bonds.[31]

5) Talks

Our work generated many invited talks at universities and conferences. As a sampling, between the time Sept. 1, 1994 and August 31, 1995, the following talks were given:

Three invited Gordon Conference talks in physics and polymer science, a talks at the North American Physical Society Meeting, the acceptance speech for the Schawlow Prize for Laser Science, an invited talk at the General Meeting of the OSA, 2 invited talks at the Am. Phys. Soc. March Meeting (one of polymers and one on atom interferometers), a APS tutorial on Laser Cooling and Trapping, an invited talk at JPL, invited talks at the APS DAMOP meeting, and the Ann. Am. Chem. Soc. Meeting, the Stevenson Lecture at Washington State Univ, the Welsch Lectures (2) at the University of Toronto, and talks at Lewis and Clark (2) and Moorehead College (2) and as part of the Laser Science Distinguished Lecturer, a speech to commemorate the founding of the Atomic and Molecular Science as a division of the Academica Sinica, and invited talk and the April meeting of the APS, an invited talk at a UCSF symposium on optical microscopy, a talk in a special session of the Int. Conf. on Laser Spectroscopy (with N. Bloembergen and C. Cohen-Tannoudji) to honor A. Gozzini and G.W. Series, another invited talk at the same conference, a talk to honor Horoshi Takuma in Tokyo, an invited talk at the Int. Symp. on the Foundations of Quantum mechanics, an acceptance speech for the Science for Art Prize in Paris, colloquium talks at the Univ. of Florence, the Max Planck Inst. for Quantum Electronics, and SLAC.

In addition, my students or postdocs gave 6 of the invited talks this academic year and Mark Kasevich gave three of the invited talks of work done in a collaboration with my postdoc, one of my graduate students and I.

Between the time Sept. 1, 1995 to August 31, 1996, a partial list includes the following talks:

A plenary talk at the Annual Rheology Conference in Sacramento; ceremonial talk to commemorate the 50th anniversary of the Fermi and Franck Institutes, Univ. of Chicago; Special colloquium to honor Prof. Tom Kinoshita's retirement, Cornell Univ.; talks at Union College, Bates College, and Hamline College as part of the Am. Phys. Soc. Distinguished Lecturer Series; talk at the National Academy of Science

Symposium at Berkeley; invited talks at the Western Spectroscopy Conf. at Asilomar; Int. Conf in Quantum Electronics, Sydney Australia; Workshop on Atom Optics and Atom Interferometry, Carins, Australia; Opt. Soc. of Am. General Meeting in Rochester; colloquia at Univ. of Minnesota, Max Planck Inst. for Quantum Electronics, Garching Germany. In addition, my students have given ~6 invited talks at various Am. Phys. Soc. conferences, Materials Science Conferences, and Gordon conferences, etc.

6) Patents

There have been 5 patent disclosures and two patents filed by Stanford during this granting period. One patent, on electronically controlled optical tweezers, is currently licensed by Stanford to Olympus. The other patent application is on a new fluorescent method on measuring the length of DNA.

6) Student and Post-doctoral training during this granting period

During this particular granting period, Steve Quake, who won the Apker Award for his honors undergraduate thesis in my lab, spent half of his time as a graduate student in my lab, and two years as a post-doc with me has been an Assistant Professor at Cal Tech since the fall of 1996. Brent Young (Ph.D., Jan. 1997) is now an NRC post-doc working in Dave Wineland's group at NIST. Tom Perkins, (Ph.D, July 1997) will begin a post-doc with Steve Block at Princeton. Perkins was awarded the Padden Prize for the best thesis in polymer science for 1997. Achim Peters will be graduating this fall after finishing the g measurement and has just begun to apply for a position.

Several undergraduate students did their honors thesis in my lab. Dolores Bozovic and Anita Goel are now graduate students in physics at Harvard. Chris Niell, winner of the Firestone Award for undergraduate research, spent two years teaching at the Menlo school and is applying to graduate school. Currently, an undergraduate, Aparna Bhatnagar is working in my lab on an atomic force microscope project.

My post-docs during this granting period are now at the following positions: Martin Weitz is now a research scientist working in Ted Hänsch's lab at the Max Planck Institute for Quantum Optics, in Garching, Germany. Nir Davidson is an Assistant Professor at the Weitzman Institute in Israel and Charles Adams is an Assistant Professor at the University of Durham, England.

All of my students and post-docs since the beginning of my career as principal investigator at AT&T Bell Laboratories are employed in careers as research physicists. Several are now tenured at prestigious research universities such as the University of Pennsylvania, the University of Tokyo and Yale University or a group leaders at IBM and NIST.

7) Awards

In recognition of the work sponsored by the AFOSR, S. Chu was received the following awards within the last three years:

Election to the Academic Sinica of Taiwan

Distinguished Traveling Lecturer of the Laser Science Topical Group of the APS

Senior Scientist award of the Humboldt Foundation

The Guggenheim Fellowship

The Science for Art Prize sponsored by LVMH (Moët Hennessy - Louis Vuitton)

The Noble Prize in Physics

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